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GENERAL DYNAMICS

Convair Division

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INFLUENCE OF CREEP DAMAGE ON THE
TOUGHNESS OF Ti-5Al-2.5 Sn AND
301 STAINLESS STEEL XFH at -423°F

MRG 250

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GENERAL DYNAMICS/CONVAIR

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SUBJECT: "Influence of Creep Damage on the Toughness of Ti-5Al-2.5Sn and 301 Stainless Steel XFH at -423°F."

ABSTRACT: The notched/unnotched tensile strength ratios of Ti-5Al-2.5Sn and 301 S.S. XFH were determined at -423°F before and after creep testing at 600°F. Creep damage was achieved by stressing both alloys at 600°F for 24 hours. Under these conditions a stress of 69,000 psi produced 0.014 in/in of creep strain for Ti-5Al-2.5Sn, and a stress of 168,000 psi produced 0.0027 in/in of creep strain for the 301 S.S. XFH. The creep damage produced in the Ti alloy reduced the low temperature notched/unnotched tensile strength ratio from 0.62 to 0.56 at -423°F. For 301 S.S. XFH the creep damage sustained at 600°F caused a reduction in notched/unnotched ratio from 0.96 to 0.86 at -423°F. These reductions in fracture toughness illustrate a trend which required verification by additional testing.

The ramifications of these observations are discussed in relation to applications such as a recoverable booster system, nuclear reactor rocket engine and reusable winged space planes.

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SUBJECT: Influence of Creep Damage on the Toughness of Ti-5Al-2.5Sn and 301 Stainless Steel XFH at -423°F.

INTRODUCTION

In many of the structural alloy applications encountered in current space programs the material has been subjected to conditions of low temperatures and high stress. Under these conditions a most vital characteristic of a structural material is its fracture toughness or resistance to crack propagation at cryogenic temperatures.

There are two general classes of variables that affect the fracture toughness of a material. One is associated with the metallurgical characteristics of the alloy and includes such factors as chemical composition, crystalline structure, microstructure, impurities, heat treatment, etc. The second class includes factors which are superimposed on the alloy by virtue of the service conditions. These include: temperature, strain rate, stress concentration factors, complexities of stress distribution, etc.

The influence of these various factors upon the fracture characteristics of structural alloys is reasonably well known on at least a qualitative basis. However, the degree to which the fracture toughness of metals is affected by these variables applied in sequence or in combination is more difficult to determine.

It is the purpose of this report to relate the results of work aimed at determining the influence of a combination of factors, heretofore not studied, on the fracture toughness of two promising high strength structural alloys. This work was carried out under REA 111-9222.

The objective of this study is to explore the influence of prior creep at elevated temperatures upon the subseqent fracture toughness at cryogenic temperatures. Creep is defined as a time dependent deformation of a material under stress at elevated temperatures. As a result of creep at elevated temperature the subsequent mechanical properties of an alloy may be altered significantly. Minute lattice defects are generated during the creep exposure which leave permanent damage in the crystalline structure. On the basis of physical metallurgical principles these defects can affect the fracture toughness of an alloy at cryogenic temperatures to a significant degree.

The consequences of lowered fracture toughness by exposure to creep at elevated temperatures are of major significance to space vehicles that are designed to be re-useable and that utilize cryogenic propellants. A typical example of such a vehicle is the concept of a "recoverable booster". In this concept the boost stage of a space ship complex is recovered aerodynamically after burnout. In the course of each flight the tank material encounters cryogenic temperatures during launch phase through use of liquid oxygen and possibly liquid hydrogen propellants and then aerodynamic heating during re-entry. The high temperature exposure during re-entry results in creep extension in the tank and wing sections of the booster vehicle. On each subsequent flight the tank material is subjected to additional cycles of cryogenic temperature exposure followed by creep extension during re-entry. If creep damage is encountered during re-entry the fracture toughness of the tank skin material at cryogenic temperatures might be reduced to a dangerously low level and could result in greatly reduced reliability during re-use of the booster.

Other examples of applications where creep damage may be a significant factor in design through this mechanism include: Space Plane, Dyna-soar, nuclear rocket boosters, and other re-usable vehicles.

MATERIALS

Two of the more promising high strength alloys were used in this investigation: Cold rolled Type 301 stainless steel sheet (Spec. GD/A 0-71004) and annealed 5Al-2.5Sn titanium alloy sheet. The chemical analyses of these alloys are given in Table I. The chemistry of the 301 S.S. conforms to the specification established for missile tank construction. However, the oxygen content of the titanium alloy exceeds the level established in Specification GD/A 0-71010, and can be expected to deleteriously affect the fracture toughness of the alloy at extreme sub-zero temperatures. The referenced specification limits the oxygen content to 0.12% and the 5Al-2.5Sn-Ti sheet alloy studied in this investigation had an oxygen content of 0.167%. This material was a commercial grade of the alloy and had not been procured to Specification GD/A 0-71010.

TEST PROCEDURES

Creep damage was accomplished by creep testing specimens having the configuration shown in Figure 1. The creep test procedure consists of placing the specimen without load into the creep furnace held at the required test temperature. Temperature equilibrium over the gage length of the specimen is achieved from ½ to 1 hour and is monitored by 3 thermocouples placed at the top, middle, and bottom of the reduced section of the specimen. After temperature equilibrium is achieved the load is applied and the creep strain is followed by a linear differential transformer having a span of .040 inch and an accuracy of ± 0.0001 in/in.

After creep testing the specimens were remachined into standard tensile coupons of smooth[1] or notched[2] configurations and tested at room temperature and -423°F using a 0.001 in/in/min strain rate to yield and 0.15 in/min head speed to fracture.

1. EMG-D-1
2. MRG-D-10 Notch A, K_t=6.3

RESULTS AND DISCUSSION

In order to establish some degree of creep damage whose influence on low temperature toughness could be evaluated, specimens of Ti-5Al-2.5Sn and 301 S.S. XFH were subjected to stresses at 600°F for 24 hours duration. The stress employed for the titanium alloy was 69,000 psi which was sufficient to cause a total creep strain of about 0.0138 in/in in 24 hours at 600°F. The creep curve determined on this alloy under the related conditions is shown in Figure 2. The 301 S.S. XFH alloy was stressed at 168,000 psi for 24 hours at 600°F. This exposure produced a total creep strain of 0.0027 in/in. The creep curve for this alloy is also shown in Figure 2. These creep deformation curves were established on the average value based on three separate tests for each alloy.

After creep exposure the samples were remachined so that they would fit the liquid hydrogen cryostat. Half of the samples exposed to creep damage at elevated temperatures were machined into notched tensile specimens (Drawing No. MRG-D-10) having a stress-concentration factor, Kt, of 6.3.

The results of the tensile tests performed on these specimens are presented in Table II for comparison.

Ti-5Al-2.5Sn

The titanium alloy did not exhibit any decrease in tensile properties at room temperature as a result of creep testing. At -423°F, however, the notched-unnotched ratio decreased from 0.62 to 0.56 as a result of creep exposure. The other properties such as smooth tensile, yield, elongation and elastic modulus seem to be unaffected by the prior creep exposure. The relatively low notched/unnotched ratio at -423°F of this alloy in the as-received condition is undoubtedly due to the high oxygen content of this alloy as discussed in conjunction with Table I. Further verification of this premise is obtained by observing the high yield strength of this particular alloy, 128.2 ksi, approximately 18,000 psi above its normally guaranteed level. This heat of the Ti-5Al-2.5Sn alloy would not be recommended for use at liquid hydrogen temperature because of its notch sensitivity in the as-received condition. While creep damage did lower its notched/unnotched strength-ratio from 0.62 to 0.56, similar testing must be performed on initially acceptable material having a notched/unnotched tensile ratio in the as-received condition in the range of 0.9 - 1.0 at -423°F before it is possible to evaluate the quantitative effect of prior creep damage on the fracture toughness of this alloy at cryogenic temperatures.

301 Stainless Steel

In the case of 301 S.S. XFH the tensile properties at room temperature were altered slightly by prior creep testing. The yield and ultimate tensile strengths increased while the elongation decreased. At -423°F the yield and ultimate strengths did not change but the elongation decreased to 0.5% and the notched/unnotched ratio decreased to 0.86 from its original level of 0.96 as a result of prior creep exposure.

Both alloys showed evidence of creep damage resulting from prolonged stressing at a temperature of 600°F.

The critical amount of creep strain necessary to produce a deleterious effect on toughness is not known at this time. However, the creep strain employed in these initial tests represents a reasonable amount that might be encountered in structures. The more quantitative aspects of the relationship between creep damage and low temperature brittle fracture resistance must await further testing. In this study it has been demonstrated that a problem area may exist in reusable cryogenic tanks subject to creep during portions of its useful life.

CONCLUSIONS

Microstructural damage produced by modest creep exposure had a deleterious effect upon the subsequent toughness characteristics of 301 S.S. XFH and Ti-5Al-2.5Sn at -423°F.

The notched/unnotched strength ratio of 301 S.S. was reduced from 0.96 in the as-received condition to 0.86 at -423°F by 0.0027 in/in of prior creep strain at 600°F.

The notched/unnotched ratio of Ti-5Al-2.5Sn was reduced from an original value of 0.62 to 0.56 at -423°F by 0.014 in/in of prior creep strain at 600°F.

TABLE I

CHEMICAL ANALYSIS OF 301 S.S. AND Ti-5Al-2.5Sn ALLOYS

	Weight Percent											
	C	Cr	Ni	Mn	Si	Ti	Sn	Al	O	N	H	Fe
301 S.S.	0.07	17.58	7.14	1.12	0.71	-	-	-	-	-	-	Bal.
Ti-5Al-2.5Sn	0.038	-	-	.05	0.167	Bal.	2.53	5.14	0.167	.023	.0084	0.18

TABLE II

EFFECT OF PRIOR CREEP ON THE TENSILE PROPERTIES AT 75°F AND -423°F OF Ti-5Al-2.5Sn AND 301 S.S. XFH ALLOYS

Alloy and Condition	F_{ty} ksi	F_{tu} ksi	e %	Modulus of Elasticity x 10^6 psi	Notched Tensile ksi	Notched/ Unnotched Ratio	Test Temp °F
Ti-5Al-2.5Sn							
As Received	128.2[1]	129.7	21.7	16.7			Room
Creep Tested[2]	128.3	133.6	21.7	17.7			Room
As Received	238.2	261.9	4.5	16.1	139.0		
	241.0	261.9	4.0	18.4	183.8		
Avg.	239.6	261.9	4.3	17.3	161.4	0.62	-423
Creep Tested	238.5	245.8	-	17.7	167.9		
	242.3	260.1	4.0	18.3	117.7		
Avg.	240.4	252.9	4.0	18.0	142.8	0.56	-423
301 S.S. - XFH							
As Received	205.5	221.9	4.8	25.1			Room
Creep Tested[3]	222.5	247.8	2.0	26.1			Room
As Received	289.6	316.6	-	22.2	290.0		
	265.0	310.2	3.5	24.1	308.8		
Avg.	277.3	313.4	3.5	23.2	299.4	0.96	-423
Creep Tested	279.6	320.1	0.5	23.7	279.4		
	273.0	321.3	-	21.3	275.9		
Avg.	276.3	320.7	0.5	22.5	277.2	0.86	-423

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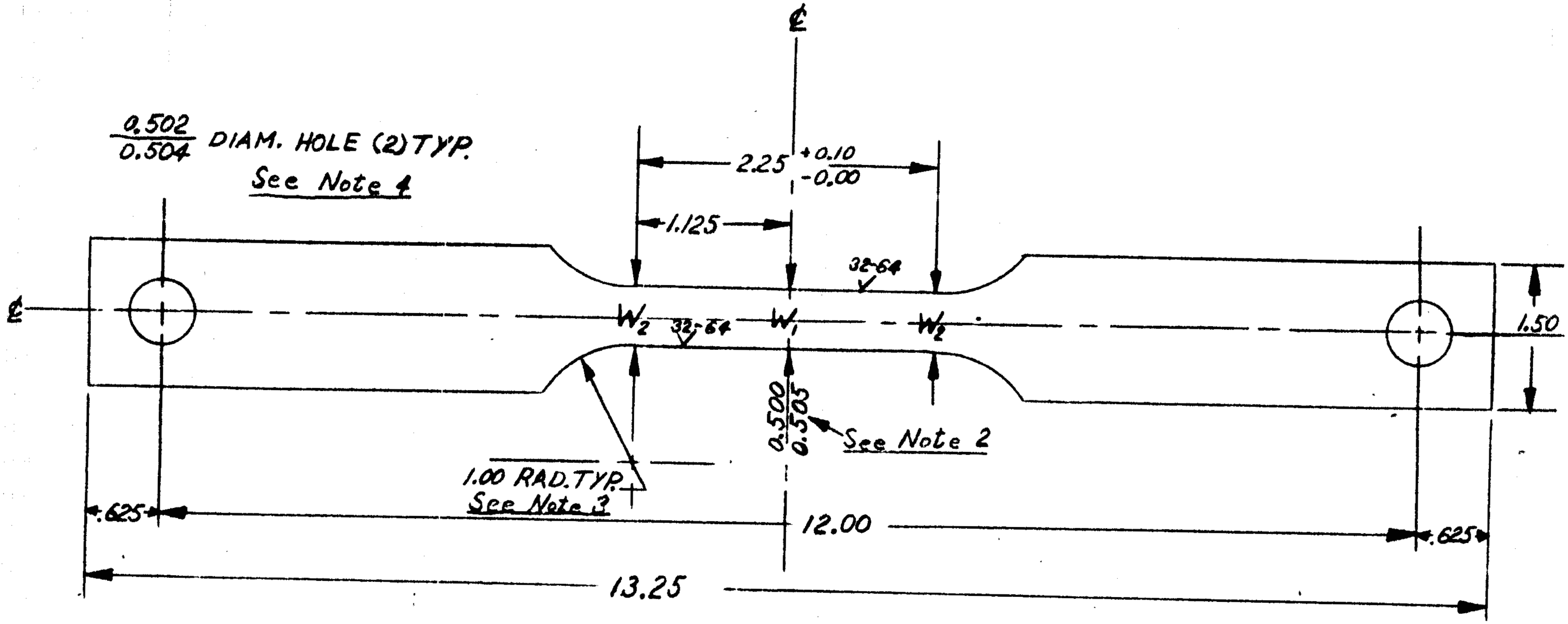
1 Values shown for all non-creep conditions represent average of 3 samples. See MRG-247.

2 Creep tested 24 hours, 69,000 psi @ 600°F, average of 3 samples.

3 Creep tested 24 hours, 168,000 psi @ 600°F, average of 3 samples.



NOTES:

1. Holes on centerline of test section within ±0.005.
2. Gradual taper from W_2 to W_1 of $0.005 {}^{+0.000}_{-0.002}$.
3. No undercut at intersection of radii and test section.

Figure 1 - Creep Specimen

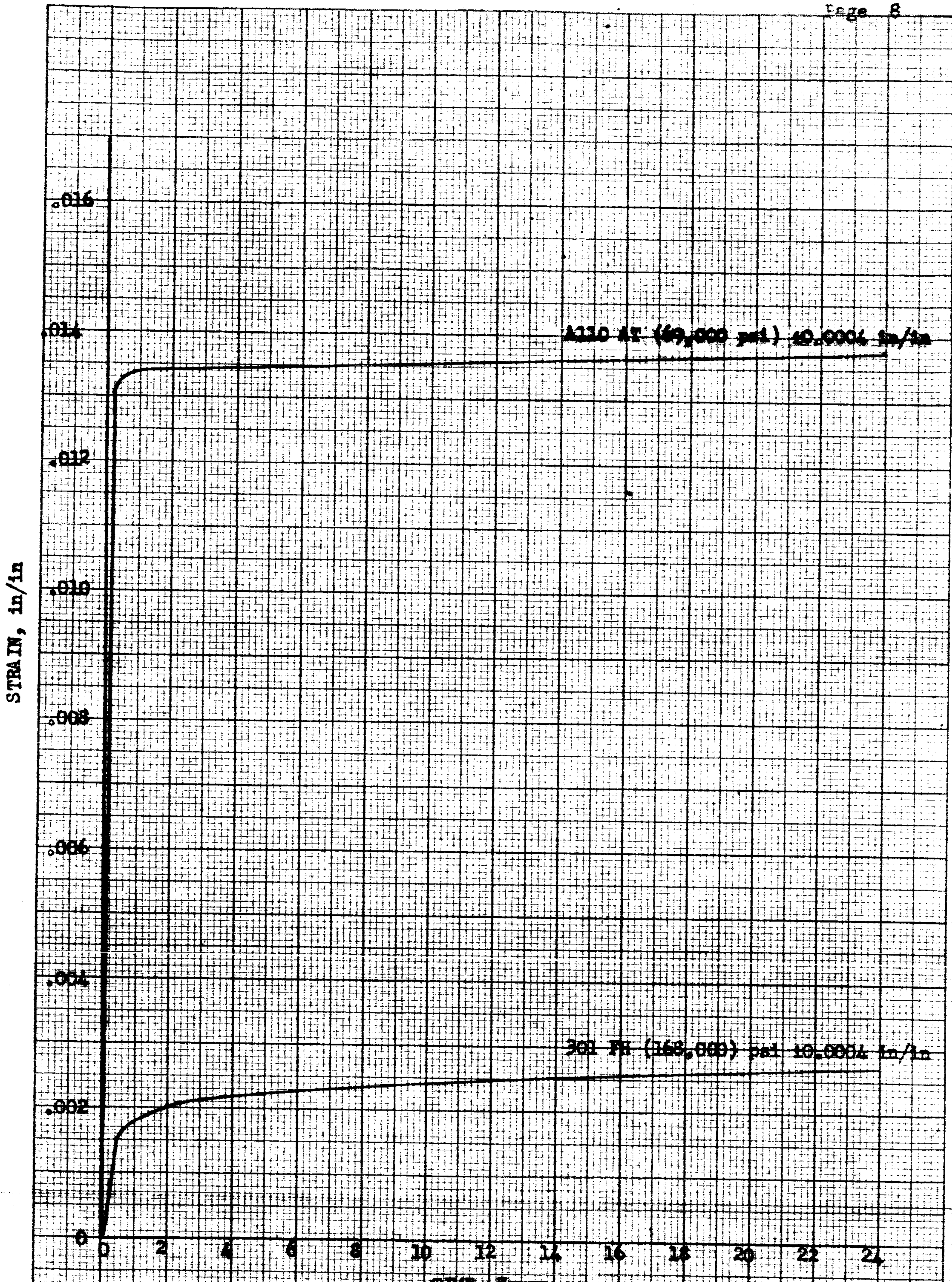


Figure 2 - Creep Curves for Ti-5Al-2.5Sn and 301 Stainless Steel XFH at 600°F

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